Biodecontamination: Cost-Benefit Analysis of A Novel Approach for Decontamination of Massive Concrete Structures

M. A. Hamilton, R. D. Rogers, L. O. Nelson
Idaho National Engineering and Environmental Laboratory

R. G. Holmes, T. N. Milner
British Nuclear Fuels plc.

A major liability facing the owners and operators of nuclear facilities worldwide is the decontamination and decommissioning of contaminated massive concrete structures. A biodecontamination technology which harnesses the action of naturally occurring bacteria is currently under joint development by BNFL and the INEEL. This emerging technology was judged to exhibit advantages in cost, worker health and safety risk reduction, and programmatic effectiveness. The process takes approximately six months to one year to remove the contaminated surface and can advantageously be applied during the Care and Maintenance phase of a D&D program. A detailed assessment of the biodecontamination process in relation to the next best and base technologies was performed. The findings of this study which recommended a large scale technology demonstration will be presented.

1 INTRODUCTION

Decommissioning and decontamination (D&D) of nuclear facilities is a huge undertaking with equally large associated costs. Within the U.S. Department of Energy alone, there are thousands of facilities currently slated for D&D and the list is growing daily. This equates to literally square miles of contaminated concrete surfaces within the DOE complex. The costs associated with these efforts is estimated in the tens of billions of dollars. The problem is not limited to the U.S

Uncoated concrete has been used for the construction of ponds, canals, sumps and other structures within operating nuclear facilities. These concrete structures have served the purpose of containment, transport, and storage of liquid and solid radioactive materials. Use of the facilities has resulted in contamination of the concrete surfaces with radionuclides. Typically this contamination is securely fixed on the surface or within the first 1 or 2 mm. Current methods for decontamination of concrete include physical and chemical removal. Such methods are costly, labor intensive, generate large volumes of waste, and pose potential risks to workers.
The task of decontaminating concrete within the large number of buildings requiring decommissioning is enormous. The difficulty of the task is increased by the continuing demands to accomplish it within more restrictive limits of waste volume, cost, and environmental risk.

Many commercial technologies for concrete decontamination have been developed and applied. Traditional concrete decontamination methods included shot blasting, mechanical scabbling, detergent scrubbing, high pressure washing, chemical treatments, strippable coatings, clamshell scrapers, brushing, vacuuming and attacking cracks with jack hammers. However, the use of explosives, jackhammers, etc. has been a problem because of high worker exposure to contamination suspended in the dust. It is evident from past experience that the primary decontamination methods used to date have been pressure-washing techniques and various types of scabbling.

A small number of innovative technologies that give promise of greater effectiveness/cost savings relative to technologies currently available for addressing the concrete decontamination problem through the D&D life cycle have been developed and are proposed for demonstration. One such innovative approach to cleaning contaminated concrete is biological remediation or biodecontamination. It has been demonstrated that biological activity can promote degradation of concrete and the mechanism of degradation has been characterized as consistent with chemical degradation (1). Microbially-influenced degradation (MID) is the premise for biological approaches for removing contaminants fixed in surface layers of concrete structures (2,3).

A microbially mediated process implicated in the degradation of concrete was first reported by Parker in 1945 (4), when thiobacilli were isolated from corroded concrete. Much of the research that followed over the next 5 decades has focused on identifying and enumerating the organisms responsible for the degradation process. The bacterially mediated process appears to be an acid dissolution of the cement matrix of concrete resulting from the production of strong mineral acids by specialized microorganisms. This bacterially mediated process is referred to as microbially-influenced degradation (MID) of concrete.

Two groups of bacteria, generally thought to induce acid corrosion are nitrifiers that oxidize inorganic nitrogen compounds such as ammonia to nitric acid and sulfur oxidizers that oxidize reduced inorganic sulfur compounds to sulfuric acid. Activity of both groups of bacteria has been related to biodeterioration of concrete (5,6). Nitrifying bacteria are usually implicated in concrete degradation in environments where sulfur oxidizers are not important because their substrate is lacking (7). A group of bacteria often associated with MID of concrete belong to the sulfur oxidizing genus *Thiobacillus*. Previous research conducted at INEEL and reports in literature (8), document that thiobacilli are aggressively involved in MID of concrete.

2 TECHNOLOGY DESCRIPTION

British Nuclear Fuels plc.(BNFL) and the Idaho National Engineering and Environmental Lab (INEEL) are working jointly under a Cooperative Research and Development Agreement to develop a technology that utilizes this naturally occurring phenomenon for removing surface material of radionuclide contaminated concrete. The technology can be described in three stages: application of microbes and nutrients; maintenance of microbial activity; and removal and packaging of surface material for waste disposal. The process is a passive one that essentially leaves the bacteria to actively degrade the cement matrix until the concrete surface material is loosened for easy removal to a desired depth. It is expected that the process will require 6-18 months for completion, depending on the depth and extent of contamination. Application of the bacteria and nutrients can be conducted in a fraction of the time required to physically remove concrete surface material. The maintenance phase, which essentially consists of environmental control, requires only minimum attention, primarily to monitor progress. Removal of the degraded surface material again results in reduced labor due to the ease of removal of the already loosened material. In addition, the depth of removal can be controlled such that the waste volume is greatly reduced. These reductions in labor requirements inherently result in lower costs and potential exposure risks to personnel. All phases can be conducted remotely if necessitated by high radiation fields.

Laboratory and proof of principal demonstrations have been conducted and optimum conditions for maximum rate of material removal have been established and are reported previously (2,3,9). Moisture is necessary for bacterial action, although the process does not require saturation and therefore no liquid effluent or secondary waste stream is produced. Optimal temperatures are between 25 and 30 degrees Celsius, however the process can continue at a reduced rate during sub-optimal conditions and can be used in shut down facilities that are not heated. In controlled experiments, initiation and maintenance of MID bacterial communities on concrete surfaces was induced. Biofilm formation, bacterial production of sulfuric acid, and formation of calcium oxide dissolution products was demonstrated (2,3). In proof of concept demonstrations, concrete reactivity with biogenic acid was demonstrated to be as high as 20 times more efficient than mineral acid dissolution alone can account for. It has been hypothesized that degradation is the result of microsite dissolution and subsequent weakening of the cement matrix between microsites. Prototype applications on both vertical and horizontal surfaces, verified that MID could be initiated and managed over a large surface area of contaminated concrete and also demonstrated that MID could be used to promote the removal of 2-4 mm of concrete surface.

Current efforts are focused on optimizing and engineering the application system to provide bacteria and nutrients to the concrete surface in a more cost and time efficient manner. The application process will promote continued bacterial activity for the duration necessary to remove the desired depth of contaminated concrete material with minimal inputs to the system. The preferred method of application involves mixing the bacteria, nutrients, and reduced sulfur source in an inert matrix that is easily sprayed on the surface, is hydrophilic, and adheres to uncoated concrete. Additionally, efforts are underway to adapt and use currently available technology for removal of the concrete debris once the bacteria have loosened the surface. Design of a complete integrated system is expected to be ready for full scale, active demonstration by 1999. A number of sites in the US are currently being reviewed to select the most appropriate demonstration opportunity for the fully developed process. Sites currently being reviewed include reactor demossissioning projects, the East Tennessee Technology Park (ETTP) and the US DOE Large Scale Demonstration and Deployment Project (LSDDP) initiative. UK based demonstration of the biodecontamination process is currently ongoing at the Sellafield Pile Chimney decommissioning project.

3 TECHNOLOGY BENEFIT ANALYSIS

Data collected from small scale demonstrations at the INEEL was used with preliminary engineering designs for application and maintenance of the process to estimate biodecontamination costs for a given area and depth of contaminated concrete. Labor and material costs for removal of the loosened material are included in the estimate, however packaging and disposal costs are not. Estimated costs for the process range from 0.3 to 5.0% of those for different physical removal methods such as scabbling. The preliminary cost estimate for biodecontamination is £1.70/m^2 (\$0.26/ft^2). The assumptions used in determining this estimate are provided in Table 1.

In view of the widespread need for an effective technique for the decontamination of extensive areas of radioactively contaminated concrete, the U.S. Department of Energy (DOE) evaluated various innovative decontamination technologies in a detailed assessment of 31 concrete decontamination technologies conducted by the Oak Ridge National Laboratory (10). The report concluded that eight of the technologies reviewed held sufficient promise to be recommended for demonstration, four of those were judged to be “highly useful”. One of the four useful technologies is biodecontamination. It was decided that prior to entering into a large-scale, radioactive demonstration, an independent assessment of the technology costs and benefits would be prudent. F. Gorschboth of BDM International, Inc. conducted a detailed cost/benefit evaluation of the biodecontamination technology (unpublished, internal report). A review of the four candidate technologies judged as “highly useful” in the DOE report indicated that sufficient cost data for comparison was lacking in one technology and the applicability of another was too limited to warrant further investigation. Consequently, a more precise assessment of the biological decontamination technology was undertaken, along with that of the remaining candidate, electro-hydraulic scabbling. Both of these technologies were compared to a base technology, scarification.

Table 1. Assumptions Used In Biodecontamination Technology Cost Estimate

Application Rate	$600m^2$/hr (6650 ft^2/hr)
Labor Rate	£30/hr ($48/hr)
Application Materials Cost	£1.65/L ($0.98/lb or $9.90/gal)
Application Material Coverage Rate	1L/9.6m^2 (1 gal/400 $ft^{2)}$
Material Removal Rate	$600m^2$/hr (6650 ft^2/hr)
Humidification requirements/operation time	10 months (7200 hrs)
Electricity Cost	$0.065/KWhr

3.1 Evaluation Technique

The technique employed for the evaluation was an adaptation of the Multi-Attribute Utility Technique (MAUT), a formal quantitative approach for analyzing decisions with regard to multiple objectives. The MAUT process as utilized in the study took the following form:

1. A set of fundamental objectives for the application of the candidate technologies were identified. These objectives established criteria for evaluating and comparing technologies.

2. A utility function was then defined to represent decision-makers preferences regarding their willingness-to-pay to achieve benefits or avoid adverse impacts with respect to conflicting objectives. According to multi-attribute utility analysis, an additive function is appropriate for aggregating impacts upon different objectives if the measures established for the objectives are additive independent.

3. Measurement scales were then developed to quantify the degree to which the technologies would achieve the objectives.

4. Benefits were then calculated using an equation in the form

$$\text{Utility} = \sum_{i=1}^{N} W_i U_i$$

where the W's are "weights" that reflect the tradeoffs managers are willing to make between objectives, and the U's reflect the tradeoffs managers are willing to make between different levels of achievement of a single objective.

In the application of the technique, each technology was evaluated against each of the objectives, measuring technology benefits rather than baseline conditions. The technique estimated the conditions that existed, first assuming that the technology had not been implemented (e.g. baseline cost), and then assuming that the technology had been implemented. The difference between the two judgements was used to measure the benefit of the technology according to each criterion.

After the technologies' impacts on the criteria were quantified, the impacts were converted into equivalent dollars based on the value judgements (weights) described above. The total benefit value of each activity was then compared to the estimated resources required to implement the technology.

In selecting the criteria by which the technologies were to be evaluated, it was recognized that most of the benefit would be achieved in meeting the requirements of two or three criteria because of the mutual inclusion or irrelevance of the other criteria. Further, only the first order effect of these criteria was calculated. Based on the areas of interest indicated in the DOE's qualitative ranking of the candidate technologies, the following objectives were identified as those against which the technologies were to be evaluated:

- Worker health and safety
- Achievement of mission (program) objective
- Realization of cost savings

3.2 Evaluation Assumptions

It is recognized that during the course of this study, various assumptions were made and certain boundary conditions were imposed. As a boundary condition of the study, the concrete contamination of a DOE facility that contains 1.8 million m^2 (20 million $ft^{2)}$ of concrete surfaces of various types, all potentially contaminated, was selected for theoretically determining the projected benefits/costs of the biodecontamination technology as opposed to the baseline technology and other selected candidate technology for demonstration. The extent and variety of concrete contamination at this facility provided an ideal test bed for the evaluation. The assumptions imposed on the analysis are summarized below.

- The decontamination of the DOE facility test bed provided a reasonable and valid arena for evaluating competing candidate technologies
- The 31 technologies determined by the DOE to be useful for concrete decontamination provided a representative set of available technologies
- The results of the initial screening of these technologies provided a reasonable mix of innovative technologies from which those suitable for demonstration could be selected
- The further screening of the technologies to those employed in the analysis was valid for technology comparison, in view of the lack of cost data and the limitations of applicability of the other technologies that were rated as highly favorable for demonstration
- The major objectives of the demonstration and adoption of innovative technologies for the concrete decontamination program are: enhanced performance of cost reduction, and lessening of work health and safety risk
- The MAUT is valid and applicable to the evaluation
- The benefit determination, based on the impacts of the candidate technologies on different objectives are additive, since the measures established for the achievement of objectives are additive independent.

3.3 Evaluation Results

As a result of this evaluation, it was concluded that the qualitatively projected advantages of the biodecontamination technology were confirmed by the more precise quantitative analysis. Specifically, the total benefits projected to accrue from the adoption of the biodecontamination technology and from the adoption of the electro-hydraulic scabbling technology compared with employing the baseline technology from analysis of the given test scenario were calculated to be:

For biological decontamination = £90.6 M ($145.0 M)

For electro-hydraulic scabbling = (-)£4.7 M ($7.5 M)

The benefits accrued from biodecontamination reflect combined benefits in risk reduction, mission achievement, and cost reduction. The negative benefits accrued from electro-hydraulic scabbling are largely a result of the negative benefit of mission achievement relative to employing the baseline technology of scarification. These results are summarized in Table 2.

Table 2. Relationship Between Technologies' Cost/Benefits And Program Objectives

Technology	Cost Components		Total Costs	Benefits/Objectives		Total Benefits
Electro-Hydraulic Scabbling	Capital Costs	Unknown	$10.7 M	Risk Reduction	$-0.0001 M	$-7.46 M
	Labor Costs	NA		Mission Achievement	$-84.0 M	
	Operating Costs	$10.7M		Cost Reduction	$75.6 M	
Biodecontamiantion	Capital Costs	Unknown	$0.22 M	Risk Reduction	$0.011 M	$145.0 M
	Labor Costs	NA		Mission Achievement	$58.0 M	
	Operating Costs	$0.22M		Cost Reduction	$87.0 M	

DISCUSSION

Biodecontamination is an innovative process that is currently being developed by the INEEL and BNFL to meet both the U.S. DOE needs and the U.K. BNFL needs for cost effective concrete decontamination. Because the depth of removal of a contaminated surface can be controlled in the application of this technology, production of secondary waste is greatly reduced and the occurrence of airborne contamination is eliminated. Estimated costs for the process range from 0.3 to 5.0% of those for different scabbling methods. As methods for application are developed, it is thought that the process will be usable for decontamination of incumbered (fitting, conduit, piping, etc.) floors and walls. Also, because of its "hands-off" operation, worker exposure to radiation and industrial accidents is expected to be greatly reduced.

Laboratory and proof of principal demonstrations have established that MID bacterial populations can be applied and maintained on large concrete surfaces and that their activity can be controlled to promote degradation for the purpose of decontamination. Systems for application, maintenance, and removal are currently being evaluated and optimized and an integrated technology is expected to be ready for demonstration in 1999.

The MAUT approach used for cost/benefit analysis provides aggregate projected benefits, both monetary and non-monetary, of adopting the biological technology compared with employing electro-hydraulic scabbling or the baseline technology of scarification. The findings of the study project significant potential cost reductions and non-cost benefits from the adoption of a biological technology for the decontamination of concrete.

REFERENCES

1. Sand, W. and E. Bock, 1984. "Concrete Corrosion in the Hamburg Sewer System", *Environmental Technology Letters*, 5, pp. 517-528

2. Benson, J. and Eccles H., 1995. "A novel technique for the decontamination of concrete and steel." Proc. ImechE, Nuclear Decommissioning International Conference. London, UK.

3. Hamilton, M. A., R.D. Rogers, and J. Benson, 1996. "Biodecontamination of Concrete". Proc. Nuclear and Hazardous Waste Management International Topical Meeting, Seattle, WA.

4. Parker, 1945 . "The Corrosion of Concrete: I. The Isolation of a Species of Bacterium Associated with the Corrosion of Concrete Exposed To Atmospheres Containing Hydrogen Sulfide", *Australian Journal of Experimental Biological Medical Sciences*, 23, p. 81

5. Kirstein, K. O., W. Stiller, and E. Bock, 1986. "Influence of Microorganisms Upon Concrete Structures", *Beton-und Stahlbetonbau*, 81 (8), pp. 202-205

6. Sand, W., 1987. "Importance of Hydrogen Sulfide, Thiosulfate, and Methylmercaptan for Growth of Thiobacilli During Simulation of Concrete Corrosion", *Applied and Environmental Microbiology,* 53, pp. 1645-1648

7. Bock, E. and W. Sand, 1993. "The Microbiology of Masonry Biodeterioration", *Journal of Applied Bacteriology*, 74:503-514

8. Sand, W. and E. Bock, 1988. "Biogenic Sulphuric Acid Attack in Sewage Systems", *Seventh International Biodeterioration Symposium,* Cambridge, England, D. R. Houghton, R. N. Smith, H. O. W. Eggins (eds.), pp. 113-117

9. Roger, R. D., M. A. Hamilton, L. O. Nelson, J. Benson, and M. Green. 1996. Evaluation of Microbially Influenced Degradation as a Method for the Decontamination of Radioactively Contaminated Concrete. *Proceedings: Materials Research Society*, 1996 Fall Meeting.

10. Dickerson, K. S., J. J. Wilson-Nicolas, and M. I. Morris, 1995. Contaminated Concrete: Occurrence and Emerging Technologies for DOE Decontamination. DOE/ORO/2034.